Optical Communications for Deep Space Missions

Keith Wilson, Jet Propulsion Laboratory
Michael Enoch, Emergent Information Technologies, Inc.

ABSTRACT

The Jet Propulsion Laboratory has had a long interest in optical communications for use in deep space exploration missions. Lasercomm technology offers the promise of significant advantages over RF in terms of communication system performance, and spacecraft mass and power savings. This paper describes the activities at JPL to evaluate optical communication systems for use on deep space exploration spacecraft.

INTRODUCTION

NASA's Strategic Plan calls for establishing a virtual presence throughout the solar system. Meeting the telecommunications bandwidth requirements of the high-resolution multispectral instruments, orbital and in situ investigations, will require the development of high-data-rate communications links for data return and dissemination As human exploration continues throughout the solar system, there will be an ongoing need to keep the public engaged. To provide TV, HDTV, and IMAX images from the planets, telecommunications systems must operate at unprecedented data rates. Yet, the economics of space flight have forced significant reductions in the sizes of the spacecraft. The paradigm in today's environment is more bandwidth for high-data-rate instruments, with less impact (mass, size, power) on the spacecraft. Meeting these seemingly conflicting requirements has driven mission designers to higher telecommunications carrier frequencies. To respond, telecommunications on Jet Propulsion Laboratory (JPL) deep space missions will have to evolve from the current X-band, to Ka-band and eventually to optical frequencies.

Free-space lasercomm technology to meet the demand for high-bandwidth, low-power-consumption, low-mass telecommunications subsystems for future NASA missions has been under development at JPL for over 15 years. The JPL deep space optical communications program focuses on system-level studies [1], theoretical analyses [2], systems development [3, 4], field demonstrations [5–7]; and the development of statistical models for atmospheric attenuation [8]. The key elements of the optical deep space link consists of a Q-switched 1 064-nm Nd:YAG laser coupled to a 10 cm or 30 cm aperture telescope (depending on data rate) transmitting to a 5–10 m ground receiver [5, 9]. The data are transmitted in the pulse position modulation (PPM) format that takes advantage of the high peak power, low average power of a Q-switched laser to obtain both wall plug efficiency and a high signal-to-noise ratio. While the uplink at the doubled Nd:YAG laser frequency offers transmit/receive isolation, the effects of atmospheric attenuation and scintillation at the shorter wavelength results in deep signal fades. Approaches such as adaptive optics compensation, multibeam transmission, and the use of longer wavelength lasers such as Yb:YAG lasers at 1030 nm are also being considered for uplink options [10, 11].

The road to deep space lasercomm will be built on the experience gained from lasercomm demonstrations with Earth-orbiting satellites. Demonstrations must focus on the reliability of the space terminal on operational scenarios that will meet the deep space coverage needs. In this article, we discuss how lasercomm compares to the X- and Ka-bands for deep space communications. We also discuss JPL's space-to-ground and ground-to-space lasercomm demonstrations that continue to allow us to calibrate the maturity of this technology and to pave the way to deep space lasercomm.

DEEP SPACE TELECOMMUNICATIONS STUDIES AND ROADMAPS

A 1994 JPL Advanced Communications Benefits Study (ACBS) compared the benefits that X-band, Ka-band, and lasercomm technologies afford to future deep space missions [1]. The baseline for comparison was the current Deep Space Network's (DSN) X-band capability. The study considered a series of hypothetical missions to Mars that required a daily return of 0.1, 1.0, or 10.0 Gb from 2.7 AU. Spacecraft terminals capable of delivering these data volumes were proposed and characterized in terms of mass, power consumption, size, and cost.

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The ACBS focused on four main areas: Technological Maturity, Operations Concept, Infrastructure Investment, and Flight Terminal Characteristics. All four considerations were weighed in terms of cost impact in order to develop a basis for comparing the costs of implementing the three options. We discuss these results and the progress made toward implementing the Ka-band and optical technologies.

Technological Maturity — X-band capability is well established at the DSN. It is mature, and continued investment contributes to improvements in capability and efficiency. Ka-band deep space capability is progressing and reaching the level of maturity needed to become the primary telecommunications link on deep space missions. Ka-band has flown on Mars Observer and Mars Global Surveyor as a Ka-band link experiment, and on DS1, and is currently flying on the Cassini spacecraft as a radio science experiment [12].

Lasercomm is not as mature as either the X- or Ka-band, and is five to ten years away from flight on a deep space mission. However, it is fast maturing, and lasercomm terminals built by the United States [13], Japan [14], and Europe [15] have been deployed in space. Although these developments add to the technology's maturity index, the deep space application is unique and will require the development of both the space terminals and the ground stations. Near-Earth demonstrations of the deep space lasercomm terminal architecture and operational strategies for achieving the required coverage will help to accelerate its acceptance on deep space missions.

The Operations Concept — X-band capability at the DSN's global complexes can provide daily 24-hour support to deep space missions. Spacecraft tracking can be negotiated and scheduled at any time, with minimal impact due to weather outages. Currently, a single DSN ground station at Goldstone supports Ka-band. To achieve comparable coverage to X-band, additional stations will need to be deployed, possibly at the DSN's complexes in Australia and Spain. In addition, Ka-band links are affected by rainfall, and additional power will need to be transmitted by the spacecraft to maintain the required at link margin and provide weather availability comparable to that of X-band.

Lasercomm links are severely affected by cloud cover, and operations strategies different from those used in the radio frequency (RF) will be needed to provide, at a minimum, the data throughput afforded by the X- and Ka-bands. One strategy is to deploy a linearly dispersed optical subnet (LDOS) of optical ground stations around the globe. This would both provide the required global coverage and mitigate the effects of cloud cover. Studies shows that eight stations so deployed would provide 24-hour coverage and 97 percent weather availability when three stations are simultaneously visible to the probe. Strategies that take advantage of the high-bandwidth lasercomm links and of advances in onboard storage can:

- Reduce the required spacecraft tracking time
- Reduce the number of ground stations needed

This can result in cost savings and at the same time provide increased data volume throughput. Other strategies proposed include an optical relay satellite in a geostationary orbit above the continental United States with an X-band downlink to the ground. This configuration can provide a near-continuous-coverage high-bandwidth link from deep space with high throughput to the ground station.

Data volume (Gb/day)	Band	Communication mass (kg)	DC power (W)	Relative cost (first unit)	Relative cost (second unit)
0.1	X-band	10.1	18.9	1.0	0.7
	Ka-band	10.0	15.2	1.0	0.7
	Optical	6.4	19.9	1.2	0.5
1.0	X-band	12.0	40.0	1.0	0.7
	Ka-band	11.3	25.0	1.1	0.7
	Optical	7.4	22.8	1.3	0.5
10.0	X-band	22.7	104.9	1.0	0.7
	Ka-band	22.5	46.0	1.2	0.8

■ **Table 1.** *X-band, Ka-band, and optical terminal comparison results.*

Infrastructure Investment — The infrastructure investment required to support the three ACBS options will depend on the operations concept. Clearly, the deployment of the LDOS will require a greater investment than that required by the Ka-band subnet to provide X-band coverage capability. A recently published NASA deep space telecommunications roadmap calls for deployment of two additional Ka-band beam waveguide antennas in 2002 and 2003. The same roadmap calls for the deployment of the first 10 m optical ground station in 2006 with the construction of a second station in 2008 [16].

Flight Terminal Characteristics — With the increase in operational frequency from X-band, to Ka-band to optical comes enhanced directivity of the transmitted beam. In general, this results in reduced flight terminal mass and power consumption for the communications link. However, at optical frequencies this is countered somewhat by lower component efficiencies, less sensitive receivers, and more stringent pointing requirements.

Comparison of the results for the three Mars telecommunications systems and for the three data volumes is presented in Table 1. Several general observations can be made from this table, namely:

- Lasercomm flight terminals have lower mass than RF systems. This ranges from 65 percent at 0.1 Gb/day down to 55 percent at 10 Gb/day, when compared with either RF terminal. Masses of the two RF terminals were approximately equal.

Characteristic	Table Mountain Facility	Starfire Optical Range
Wavelength (nm)	532	532
Pulse energy (mJ)	250	350
Repetition rate (Hz)	15–30	10
Pulse Width (nsec)	12	15
Beam Divergence (μrad)		
Days 1–4	110	80
Days 6–8	60	40
Telescope mirror diameter		
Primary (m)	0.6	1.5
Secondary (m)	0.2	0.1
Optical train transmission (percent)	60	43

■ **Table 2.** *GOPEX experiment transmit data.*

- Ka-band power requirements range from 80 percent at 0.1 Gb/day down to 40 percent at 10 Gb/day lower than X-band. Lasercomm uses slightly less power than Ka-band, except at the lowest data volume. At 0.1 Gb/day, the optical power requirement is dominated by the overhead of the acquisition/tracking subsystem, and the power consumption is approximately equal to the X-band.
- Cost of the first lasercomm flight unit is comparable to that of the X-band, Ka-band at 0.1 Gb/day, and increases gradually with data volume. Both the cost of the first unit and the uncertainty in this cost are expected to decrease as the technology matures. The cost of flight unit 2 is modestly lower than unit 1 for the RF terminals and is markedly lower for lasercomm.

The Optical Communications Telescope Laboratory

To support its future lasercomm demonstrations, NASA/JPL is building a 1 m Optical Communications Telescope Laboratory (OCTL) transceiver station at its Table Mountain Facility (TMF) in the San Gabriel Mountains of Southern California [17]. TMF is at a 2.29 km elevation and has typical atmospheric seeing of 1.5–2.0 s of arc. The telescope is being built by Brashear-LP of Pittsburgh, Pennsylvania and first light is expected in August 2001. Designed as a multipurpose instrument, the telescope will be capable of supporting future astrometry and asteroid survey research. However, the principal function of OCTL will be to support NASA's lasercomm technology development and future demonstrations.

Key goals for OCTL are to:

- Conduct communication experiments and demonstrations with laser-bearing spacecraft from low Earth orbit (LEO) to deep space
- Develop optical spacecraft communications technologies, with an emphasis on deep space applications

Lasercomm Demonstrations

Small size, low mass, low power-consumption, and high communications bandwidth are lasercomm's key advantages to deep space missions. JPL has thus sought and continues to seek opportunities for field demonstrations of this technology to better evaluate its application to its future missions. To better understand some of the challenges of lasercomm links, JPL has performed deep space (Galileo Optical Experiment, GOPEX [6]) and the near-Earth (Ground Orbit Lasercom Demonstration, GOLD) [7] experiments. These experiments demonstrated precise ground-to-space laser beam pointing and bidirectional optical links, and are described in greater detail below.

JPL is currently involved in the Ballistic Missile Defense Organization (BMDO) STRV-2 LEO-to-ground lasercomm demonstration [13], using the lasercomm terminal built by AstroTerra Corp. The experiment plans call for demonstrating a minimum of 155 Mb/s optical downlink. This demonstration would represent the highest lasercomm space-to-ground data rate to date. The STRV-2 lasercomm terminal has been successfully tested in the laboratory at 500 Mb/s on each of its two orthogonally polarized channels. Operated in this mode, it would generate an aggregate downlink rate of 1 Gb/s. Over the next several years other planned U.S. and international demonstrations at data rates ranging from 1–2.5 Gb/s [18, 19] will increase the maturity of lasercomm, and reduce the technology risk of deploying lasercomm systems in deep space.

Galileo Optical Experiment

The Galileo spacecraft's second flyby of Earth, part of the Venus-Earth-Earth Gravity Assisted (VEEGA) trajectory, afforded a unique opportunity to perform a deep space optical uplink with the spacecraft as it receded from Earth on its way to Jupiter. The sun-Earth-probe angle after the flyby was approximately 90°. This allowed the spacecraft to "look" back at the Earth and "see" a half-illuminated Earth image. This geometry allowed laser beams transmitted against a dark Earth background to provide excellent contrast at the camera. GOPEX was conducted December 9–16, 1992 from transmitting sites at the JPL Table Mountain Facility (TMF) Wrightwood, California and at the Air Force Starfire Optical Range (SOR), Kirtland Air Force Base, New Mexico. Uplinks, (Table 2), to Galileo occurred between 3:00 a.m. and 6:00 a.m. PST. The spacecraft's solid-state imaging (SSI) camera was used to detect the laser uplink.

Key experiment objectives were to:

- Demonstrate blind pointing capabilities applicable to an optical uplink to a spacecraft in deep space based solely on spacecraft ephemeris predicts
- Demonstrate the acquisition of the temporally modulated optical signal
- Validate theoretical models developed to predict the performance of the optical link
- Evaluate the optical uplink performance at 532 nm and 1.064 nm.

The 1.064 nm uplink was not performed because of the low sensitivity of the SSI camera to the IR.

The nighttime uplink had the advantage of allowing camera exposure times up to 800 ms. This facilitated the identification of the detected laser transmissions. By scanning the camera across the Earth, parallel to the Earth's terminator, during each exposure, the laser signal was readily distinguished from spurious noise counts in the camera frame. With this strategy, the laser uplink appeared as a series of evenly spaced bright dots within the camera frame, quite distinct from other features in the frame (Fig. 1).

The GOPEX laser uplink was detected on the first day at a distance of 600,000 km. When the experiment ended on December 16, the range to the spacecraft was 6,000,000 km. Images of laser uplink were received on each of the seven days of the experiment, and the laser uplink was detected on 48 of the 159 GOPEX frames taken. The demonstration extended over eight calendar days, but other spacecraft activities precluded laser transmissions on day 5. Unanticipated pointing bias in the spacecraft's scan platform resulted in no detection on frames with exposure times less than 400 ms. Inclement weather, aborted transmissions, and restrictions imposed by regulatory agencies accounted for the loss of data on the remaining frames.

THE GROUND TO ORBIT LASERCOM DEMONSTRATION

The National Space Development Agency of Japan (NASDA) launched the ETS-VI spacecraft into orbit on August 28, 1994, into what was to be a geostationary orbit above Japan. A malfunction of the apogee kick motor resulted in the satellite being left in geo-transfer orbit. To make maximum use of the spacecraft's lasercomm terminal while in this orbit, researchers at the Japanese Communications Research Laboratory (CRL) encouraged ESA and NASA researchers to use the terminal for technology demonstrations. After confirming that its existing astronomical telescopes at its TMF site could adequately track the ETS-VI satellite near apogee, JPL designed and developed the optical ground stations to support the demonstration. The GOLD experiment, conducted between ETS-VI spacecraft and the TMF ground stations, was the first demonstration of a bidirectional ground-to-space optical link.

Key GOLD experiment objectives were to:

- Demonstrate two-way spatial acquisition/tracking of laser beams with a spacecraft
- Demonstrate the first use of multiple uplink laser beams to mitigate the effects of atmospheric scintillation
- Accomplish one-way and two-way optical data transfer to a spacecraft and measure bit error rates
- Validate lasercomm link performance predictions
- Accumulate 10 elapsed hours of transmission and reception experience
- Compare downlink atmospheric transmission losses with similar data from the TMF Atmospheric Visibility Monitoring (AVM) observatory

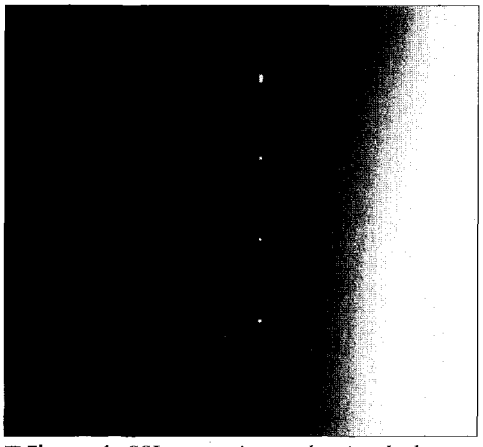

Figure 1. *SSI camera image showing the laser uplink detection from the TMF (15 Hz repetition rate, on the left) and the SOR (10-Hz repetition rate, close to the terminator) on Day 2 of GOPEX.*

Designed for a geo-to-ground communications demonstration, the Laser Communication Equipment (LCE) coarse tracking mechanism could support only apogee transits over the ground station. These occurred every third day. GOLD was performed in two phases. The first was from October 30, 1995 to January 13, 1996. During this phase the satellite transited TMF at apogee in the terminator mode. The second phase extended from March 21 to May 26, 1996. Satellite apogee passes during May occurred in the daytime. The passes were initially about 3 hr in duration; this was increased to about 5 hr after a satellite maneuver by NASDA on November 25 adjusted the satellite's orbit to facilitate demonstration from JPL.

The outage between mid-January and mid-March occurred because during this time the satellite was in the Earth's shadow at apogee. To conserve power, NASDA limited the use of the spacecraft to those activities essential to maintaining the spacecraft health for the possible second phase. Because the spacecraft transited the Van Allen radiation belts on each orbit, it was uncertain whether it would be still able to generate power for a second phase demonstration opportunity. NASDA continuously monitored the spacecraft power generating capability of the solar panels as it degraded from the electron bombardment in the Van Allen belts.

There were 44 apogee satellite passes over TMF during the two phases. On 24 of these passes, both uplink and downlink signal detections were accomplished. On four other passes only the uplink was detected. Inclement weather, hardware failures, satellite attitude control, and other miscellaneous problems accounted for the lack of link on the remaining passes.

The ground stations were the TMF 0.6 m and 1.2 m telescopes. An Argon Ion laser was coupled to the 0.6 m telescope to transmit a 1.024 Mb/s Manchester-coded pseudo-noise sequence to the

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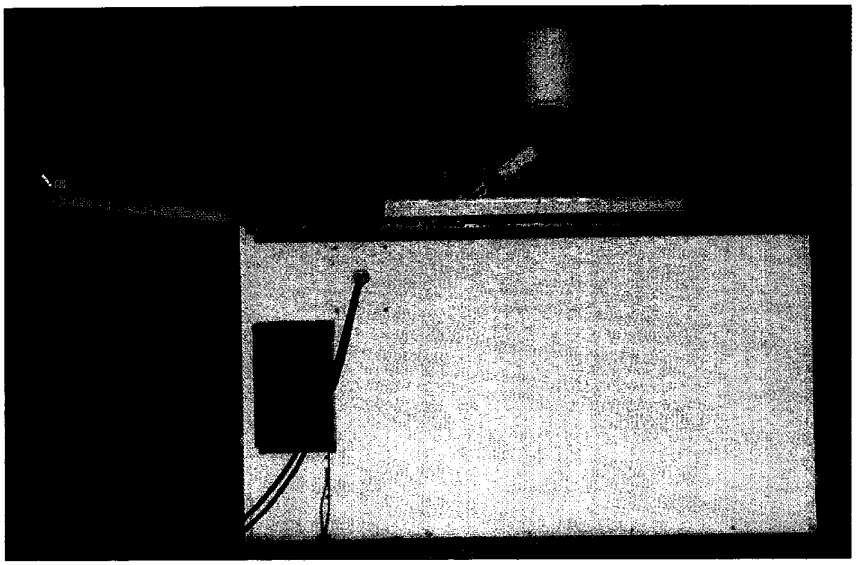

■ **Figure 2.** *The autonomous visibility monitoring station uses stars to measure atmospheric transmission at key lasercomm wavelengths; the station operates in both daytime and nighttime.*

spacecraft. The AlGaAs laser 1.024 Mb/s downlink from the satellite was detected at the 1.2 m ground receiver located approximately 60 m from the transmitter site. Downlinked PN data enabled measurement of bit error rates. Bit error rates as low as 10E–4 were measured on the uplink and 10E–5 on the downlink. Measured signal powers (corrected for measured atmospheric attenuation) agreed with theoretical predictions.

Atmospheric Visibility Monitoring

JPL has built three atmospheric visibility monitoring (AVM) stations that measure both the daytime and nighttime atmospheric transmission at key laser communications wavelengths (1064 nm, and 532 nm) [8]. A picture of one of the stations is shown in Fig. 2. These data have enabled us to improve our understanding of the long-term statistics atmospheric attenuation and its impact on the optical link. The stations are located at Mt. Lemmon, Arizona, Table Mountain, California, and Goldstone, California, and operate autonomously and continuously, measuring the brightness of selected stars in six wavelength bands. Narrowband interference filters are used to measure transmission at 532 nm and 1064 nm, and at 860 nm. Astronomical filters at the V, R, and I bands measure the transmission at these wavelengths, and the data are used as a reference for the narrowband filter measurements.

The Optical Communications Demonstrator

The JPL Optical Communications Demonstrator (OCD) is a simple design that takes advantage of the fast subwindow array reading capabilities of the new silicon focal plane arrays to accomplish both acquisition and tracking using a single array [3]. Both the received beacon and the internal reference beam (a retro-reflected portion of the transmitted beam) are focused on the array. Because the transmitted signal must be offset from the direction of the received signal, the single focal plane arrangement readily allows for this point-ahead. The relative location of the laser spots in the focal plane is a measure of the point-ahead angle. In the design, the full field of the array is read during the beacon acquisition phase. During the tracking phase, a subwindow around the beacon and transmitted images is read at kilohertz rates to close the tracking loop around a single high-bandwidth two-axis fine steering mirror. The high subarray read rates allows the fine steering mirror servo loop to suppress the effects of spacecraft jitter.

The original optical design of the terminal supported only unidirectional space-to-ground telecommunications links. However, the design has since been modified to support bidirectional links at various wavelengths, such as 1550 nm, where scintillation and attenuation effects of the atmosphere are significantly less severe. InGaAs and HgCdTe focal plane arrays and high-speed InGaAs avalanche photodiode detectors (APDs) will replace silicon arrays and APDs. Operation at these wavelengths will support the gigabits-per-second data rates planned for downlinks from Earth-orbiting satellites.

At JPL we are in the early stages of developing a detailed optical communications roadmap for flight terminal development. The plan is to first deploy 10 cm OCD on a UAV, and subsequently fly it on the International Space Station [18] (Fig. 3). The next phase of the plan will explore deploying a 30 cm aperture version of the terminal on a geostationary satellite, and subsequently deploying the deep space version on a Mars mission. These experiments will add to the experience base of this technology, and improve our understanding and the confidence in the capability of lasercomm to meet the demand for high-data-rate deep space communications.

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References

[1] H. Hemmati *et al.*, "Comparative Study of Optical and Radio Frequency Communication Systems for a deep space Mission," JPL TDA Prog. Rep. 42-128, Feb., 1997.

[2] M. Jeganathan, G. S. Mecherle, and J. R. Lesh, "Free-space Optical Communications Analysis Software," *Free-Space Laser Commun. Tech. X, SPIE*, vol. 3266, Jan. 1998.

[3] C-C. Chen and J. R. Lesh, "Overview of the Optical Communications Demonstrator," *Proc. SPIE OE-LASE '94*, vol. 2123. Jan. 1994.

[4] G. Ortiz, J. Sandusky, and A. Biswas, "Design of the Opto-Electronic Receiver for Deep Space Optical Communications," *Free-Space Laser Commun. Tech. XII, SPIE*, vol. 3932, Jan. 2000.
[5] H. Hemmati *et al.*, "High-Efficiency Pulsed Laser Transmitters for deep space Communication," *Free-Space Laser Commun. Tech. XII, SPIE*, vol. 3932, Jan. 2000.
[6] K. E. Wilson, J. R. Lesh, and T-Y. Yan, "GOPEX: A Laser Uplink to the Galileo Spacecraft on its Way to Jupiter," *Free-Space Laser Commun. Tech. V, SPIE*, vol. 1866, Jan. 1993.
[7] K. E. Wilson *et al.*, "Overview of the Ground-To-Orbit Lasercom Demonstration," *Free-Space Laser Comm. Tech. IX, SPIE*, vol. 2990, Jan. 1997.
[8] M. Jeganathan and N. Jalai, "Analysis of Data from the Atmospheric Visibility Monitoring (AVM) Program," *Free-Space Laser Comm. Tech. X, SPIE*, vol. 3266, Jan. 1998.
[9] K. Shaik, "Parameter Uncertainties for a 10-meter Ground-Based Optical Reception Station," JPL TDA Prog. Rep. 42103, Nov. 1990.
[10] M. Jeganathan *et al.*, "Data Analysis Results from the GOLD Experiments," *Free-Space Laser Comm. Tech. IX, SPIE*, vol. 2990, Feb. 1997.
[11] K. E. Wilson *et al.*, "Results of the Compensated Earth-Moon-Earth Retroreflector Laser Link (CEMERLL) Experiment," JPL TDA Prog. Rep., Nov. 1997, p. 42-131.
[12] E. Archer *et al.*, Cassini Mission: Deep Space Telecommunications into the Next Century, http://www.jpl.nasa.gov/techreport/1996/960131.rfr.html, JPL Technical Report, 1996.
[13] I. Kim *et al.*, "(Very) Preliminary Results of the STRV-2 Satellite-to-ground Lasercom Experiment," *Free-Space Laser Comm. Tech. XII, SPIE*, vol. 3932, Jan. 2000.
[14] K. Nakagawa, A. Yamamoto, and M. Toyoda, "Performance Test Result of LUCK (Laser Utilizing Communications Equipment) Engineering Model," *Free-Space Laser Comm. Tech. XII, SPIE*, vol 3932, Jan. 2000.
[15] T. Tolker-Nielsen, B. Demelenne, and E. Desplats, "In Orbit Test Results of the First SILEX terminal," *Free-Space Laser Comm. Tech. XI, SPIE*, vol. 3615, Jan. 1999.
[16] C. D. Edwards, Jr. *et al.*, "NASA's deep space Telecommunications Road Map," TMO PR 42-136, Feb. 15, 1999.
[17] K. E. Wilson, M. Britcliffe, and N. Golshan, "Progress in Design and Construction of the Optical Communication Telescope Laboratory (OCTL)," *Free-Space Laser Comm. Tech. XII, SPIE*, vol. 3932 Jan. 2000.
[18] J. Sandusky *et al.*, "Overview of the Preliminary Design of the Optical Communications Demonstration and High Rate Facility," *Free-Space Laser Comm. Tech. XI, SPIE*, vol. 3615, Jan. 1999.

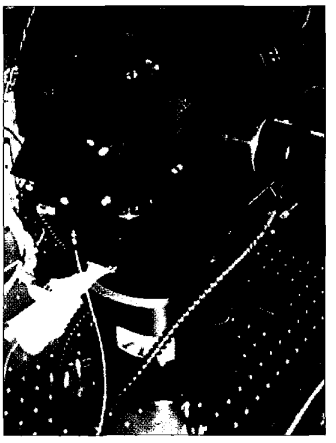

Figure 3. *The JPL optical communications demonstrator with gimbal as configured for a LEO-to-ground link. The terminal uses a single focal plane for acquisition and tracking. Modest modifications to the basic optical train architecture will enable the terminal to support bi-directional links from LEO to deep-space ranges.*

[19] Y. Arimoto, "Study on High-Speed Space Laser Communications Using Adaptive Optics and the Demonstration Experiment on International Space Station;" to be published.

BIOGRAPHIES

KEITH WILSON (kwilson@jpl.nasa.gov) received his B.Sc.(Hons) from California State Polytechnic University, Pomona, and M.A. and Ph.D. degrees from the University of Southern California, all in physics. He held several positions in industry and academia before joining JPL in 1988. In 1989 he was appointed task manager for the Galileo Optical Experiment (GOPEX), and in 1992 successfully led a team of JPL and AFRL researchers to demonstrate the first laser beam transmission to a spacecraft in deep space. In 1995 he was appointed manager for GOLD (Ground-to-Orbiter Lasercom Demonstration) and along with a team of CRL, NASDA, and JPL researchers demonstrated from JPL's Table Mountain Facility the first bidirectional optical communications link with at spacecraft at geostationary ranges. He has published over four dozen papers in laser physics, integrated optics, and optical communications, and holds three U.S. patents in fiber optic gyroscope technology. He is currently JPL task manager for the STRV-2 lasercom demonstration and technical manager for the NASA/JPL Optical Communications Telescope Laboratory. He is a member of SPIE and OSA.

MICHAEL ENOCH [M] (michael.enoch@emergent-IT.com) is a senior member of technical staff of the Advanced Programs Division of Emergent Information Technologies, Inc. He is currently involved in development of systems and operations support for small spacecraft and providing system engineering support to the U.S. Air Force Research Laboratory. He has been involved in the system engineering of military and commercial satellite and terrestrial communication systems for over 12 years. His experience ranges from the small scale, such as testing of VSAT systems and equipment, to the very large scale, such as development of frequency planning and management software for INTELSAT. His involvement with laser communications is relatively recent and a result of his involvement a development of a concept for laser communications to an airborne platform performed as part of the Lasers and Space Optical Systems (LASSOS) study for the Air Force Research Laboratory. He is a member of the IEEE Communications Society Space & Satellite Communications Technical Committee, Aerospace & Electronic Systems Society, Lasers & Electro-optics Society, and Signal Processing Society. He is also a member of the AIAA Satellite Communications Technical Committee. He holds a B.S. in engineering science from Rensselaer Polytechnic Institute, Troy, New York.

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